The Impact of Radiation Exposure upon Lithium-ion Batteries for Future Planned NASA Missions to Europa

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Outline

- ***Background***
- ***Objective and Approach***
- ***Evaluation of E-One Moli ICRM and LG Chem MJ1 Cells***
  - ***Impact of γ-ray irradiation on capacity and impedance***
  - ***100% DOD cycle life testing at +30^{o}C***
  - ***Discharge rate capability at different temperatures***
- ***Performance testing of 8-cell strings***
  - ***Impact of γ-ray irradiation upon performance***
  - ***Acceptance testing at different rates and temperatures***
  - ***Cell voltage dispersion characteristics***
- ***Qualification testing of ABSL 8s16p module***
  - ***Impact of γ-ray irradiation upon performance***
  - ***Environmental testing***
- ***Conclusions***

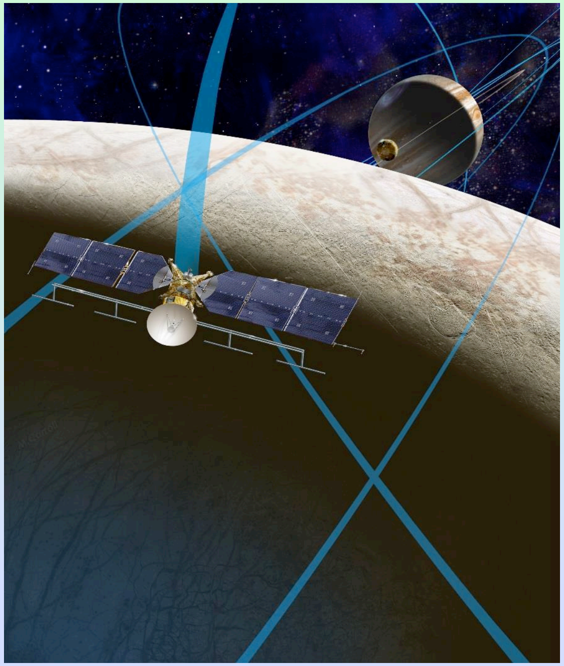
NASA's Planned Europa Clipper Mission

- Anticipated Launch Date: TBD (2020's)

- NASA's planned Europa mission would conduct a detailed reconnaissance of Jupiter's moon Europa and to investigate its habitability for life.
- The mission would send a radiation tolerant spacecraft into a long, looping orbit of Europa to perform repeated close flybys.

- Planned NASA-selected Instruments:.

1) Plasma Instrument for Magnetic Sounding (PIMS)
2) Mapping Imaging Spectrometer for Europa (MISE)
3) Europa Imaging System (EIS)
4) Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON)
5) Europa Thermal Emission Imaging System (E-THEMIS)
6) Mass Spectrometer for Planetary Exploration/Europa (MASPEX)
7) Ultraviolet Spectrograph/Europa (UVS)
8) Surface Dust Mass Analyzer (SUDA)



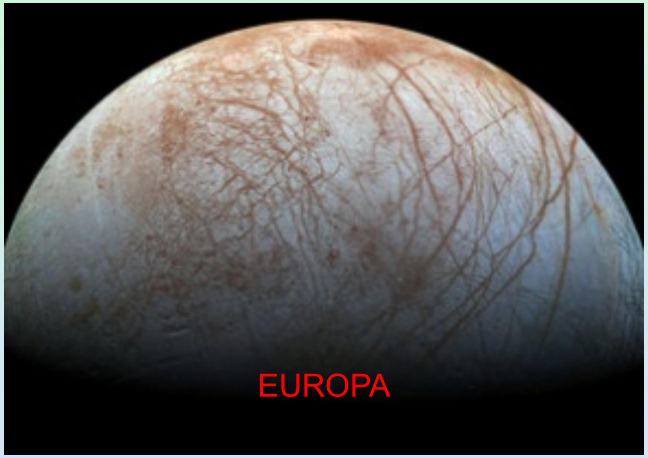
Artist's concept Image courtesy NASA/JPL-Caltech

Key Driving Battery Requirements

- Long life = 11 years (long cruise period)
- High radiation tolerance
- High specific energy
- Operating Temperature Range: 0° to +30°C
- The preliminary architecture for the Europa mission is to use a battery design consisting of high specific energy small 18650-size Li-ion cells, to capitalize on their internal safety functions, high capacity, and excellent cell-to-cell reproducibility.

Impact of Radiation Upon Li-Ion Cells

- **Li-ion batteries with resilience to radiation is desired to enable future missions.**
- Jupiter is surrounded by an enormous magnetic field and charged particles are trapped in the magnetosphere and form intense radiation belts ten time stronger than Earth's Van Allen belts.
  - Inherent resilience of the lithium-ion battery is preferred compared to radiation shielding.



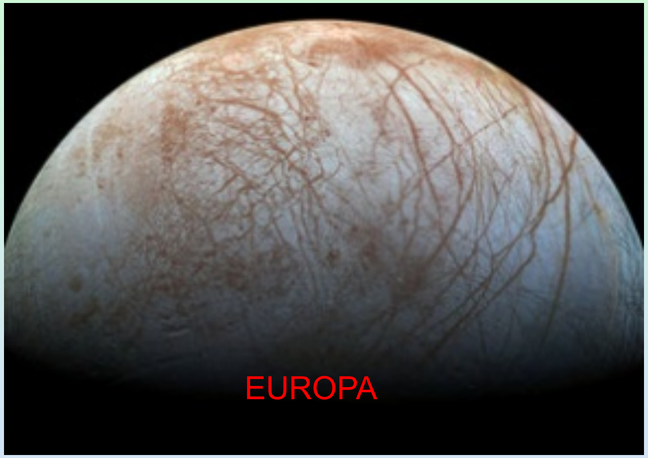
- Due the inability to subject Li-ion batteries to dry heat microbial reduction (DHMR), which involves unacceptably high temperatures, exposure to gamma-rays is a preferred technique to reduce the overall bio-burden of the battery.
  - Irradiation with ^{60}Co γ-rays can be utilized to meet planetary protection requirements.
  - Efficient sterilization procedure.

Planet	Magnetic Field Strength (vs Earth)
Earth	1
Saturn	600
Jupiter	20,000
Uranus	50
Neptune	25

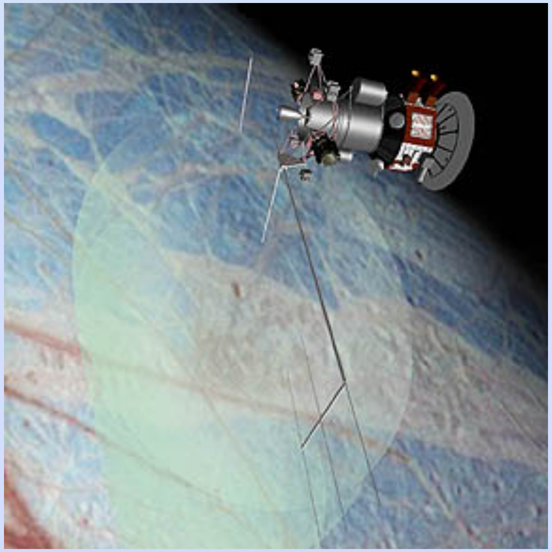
- **To meet future mission requirements, we need to demonstrate cell and battery compatibility with high levels of radiation.**

Impact of Radiation Upon Li-Ion Cells

- **Potential concerns with high radiation exposure:**
  - Decreased capacity
  - Increased cell impedance
  - Reactivity of organic electrolyte
  - Loss of separator integrity
  - Electrode delamination
  - Loss of functionality of electrochemically inert materials comprising battery design



- **Previous studies at JPL have demonstrated good resilience to ^{60}Co γ-rays:**
  - Yardney 7 Ah NCO-based cells[1]
  - Saft 9 Ah NCA-based cells[1]
  - Sony HC 18650 LCO-based cells[2]
  - Panasonic NCRA and NCRB cells[3,4]
  - E-One Moli ICRM cells[3,4]



- **The ^{60}Co γ-rays were determined to effectively simulate the high energy electrons and ions in the environment around Jupiter.**

1) B. V. Ratnakumar, et al., JES., 151 (4), A652-A659 (2004).
2) B. V. Ratnakumar, et al., JES, 152 (2), A357-A363 (2005).
3) F.C. Krause,et al., 227th ECS Meeting, Chicago, IL, May 28, 2015.
4) M. C. Smart,et al., 232nd ECS Meeting, National Harbor, MD, Oct.5, 2017.

Objective

- Demonstrate the resilience of 18650-size Li-ion cell to high levels of γ-ray irradiation.
- Demonstrate the resilience of a large capacity, aerospace quality battery module to high levels of radiation.
- Assess the viability of using ^{60}Co γ-rays as a means of reducing the bio-burden of the battery and meeting planetary protection requirements.

Approach

- Subject candidate 18650 cells to high levels of ^{60}Co γ-rays (up to 20 Mrads)
  - E-One Moli ICRM Cells
  - LG Chem MJ1 Cells
- Subject irradiated cells to electrical performance characterization testing.
  - Cycle life testing under various conditions
  - Discharge and charge rate testing
  - Impedance characterization
- Subject high capacity, aerospace quality battery module (ABSL 8s16p) to high levels of ^{60}Co γ-rays (up to 20 Mrads)
  - Functional characterization
  - Electrical characterization
  - Full battery qualification, including random vibration, shock, and thermal vacuum testing
  - Post radiation and post-environmental testing characterization

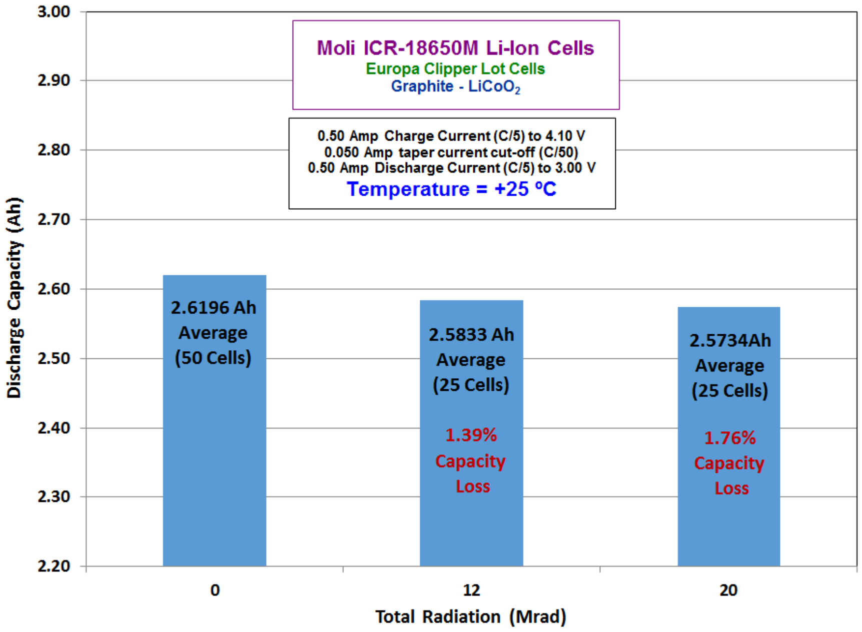
NASA's Planned Europa Clipper Mission:
Lithium-Ion 18650 Cell Chemistry Assessment

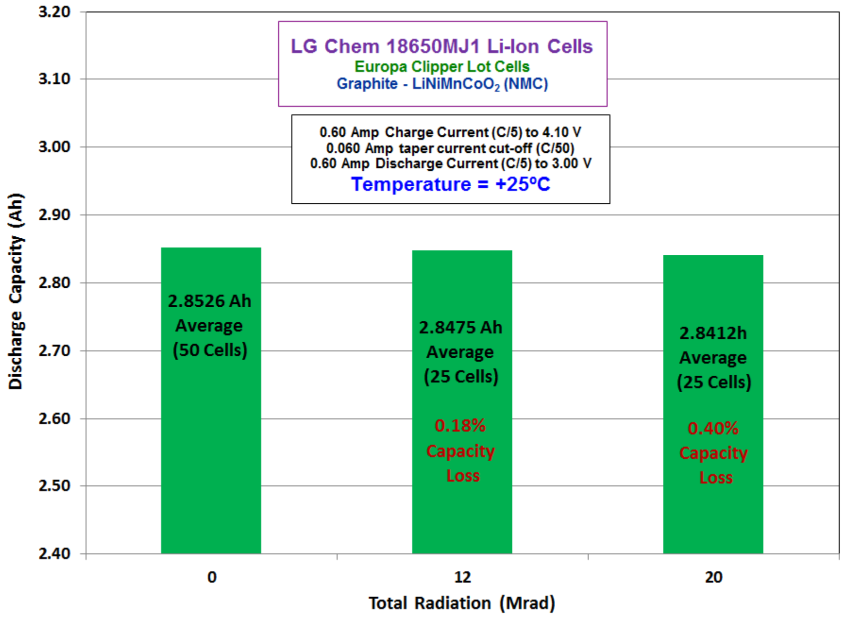
- The Europa Mission has identified a number of viable small cell Li-ion options that are good candidates for the project, which provide high specific energy and good performance characteristics.
  - LG Chem MJ1 18650 Cells
  - Molicel ICR-M 18650 Cells
  - Molicel ICR-J 18650 Cells
  - Panasonic NCR-A 18650 Cells
  - Panasonic NCR-B 18650 Cells

- An in-house performance assessment program has been initiated to determine the viability for the Europa project, which includes the following:
  - Cycle life performance under various conditions
  - Storage life testing at the cell level (at 0°C and +25°C)
  - High temperature storage characterization (+30°C)
  - 8-Cell module 100% DOD cycle life testing at +20°C
  - 8-Cell module long term storage life testing at +0°C
  - Discharge and charge rate characterization testing
  - Radiation tolerance (subjected to ^{60}Co gamma rays)

NASA's Planned Europa Clipper Mission:
Li-Ion Cell Level Testing: Impact of Radiation Exposure

- ***Impact of ^{60}Co γ-Ray Irradiation: Reversible capacity at +25°C***
  - ***Comparison of Moli ICRM and LG Chem MJ1 18650-size cells***



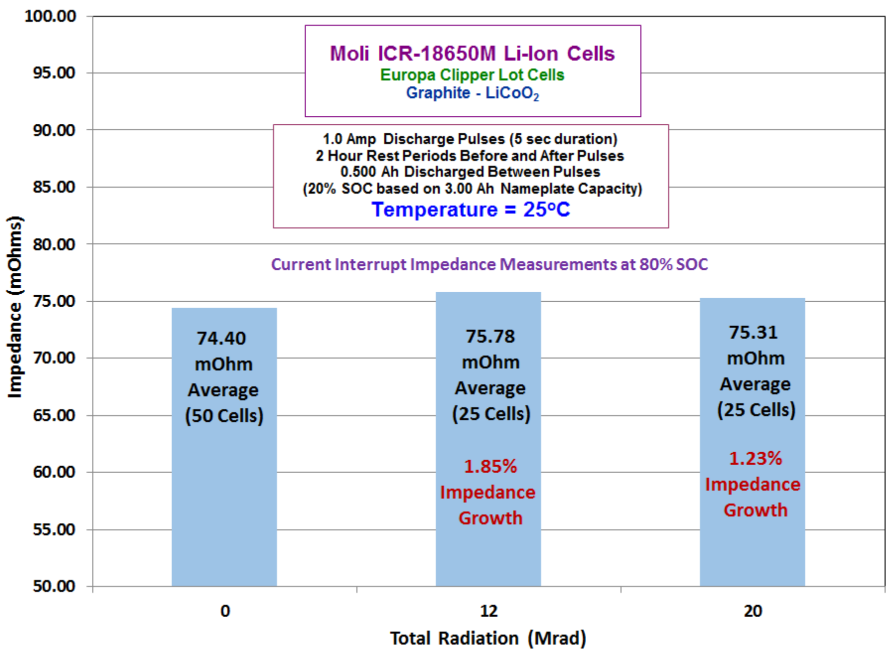


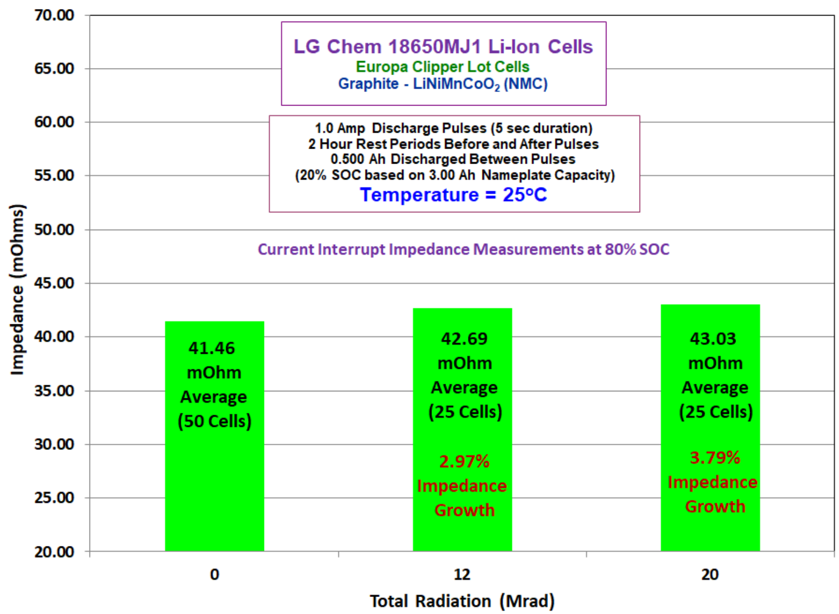
- Both cell types exhibit good resilience to high levels of radiation.
  - Only 1.76% capacity loss observed at 25°C with Moli ICRM cells when exposed to 20 Mrad TID
  - Only 0.40% capacity loss observed at 25°C with LG Chem MJ1 cells when exposed to 20 Mrad TID

NASA's Planned Europa Clipper Mission:

Li-Ion Cell Level Testing: Impact of Radiation Exposure

- **Impact of ^{60}Co γ-Ray Irradiation: Cell impedance at +25°C (80% SOC)**
  - **Comparison of Moli ICRM and LG Chem MJ1 18650-size cells**

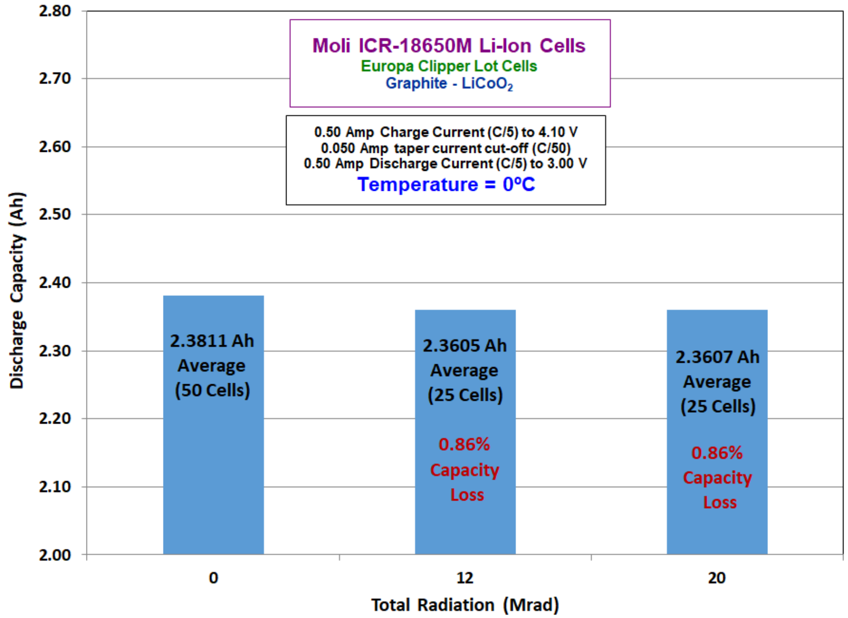


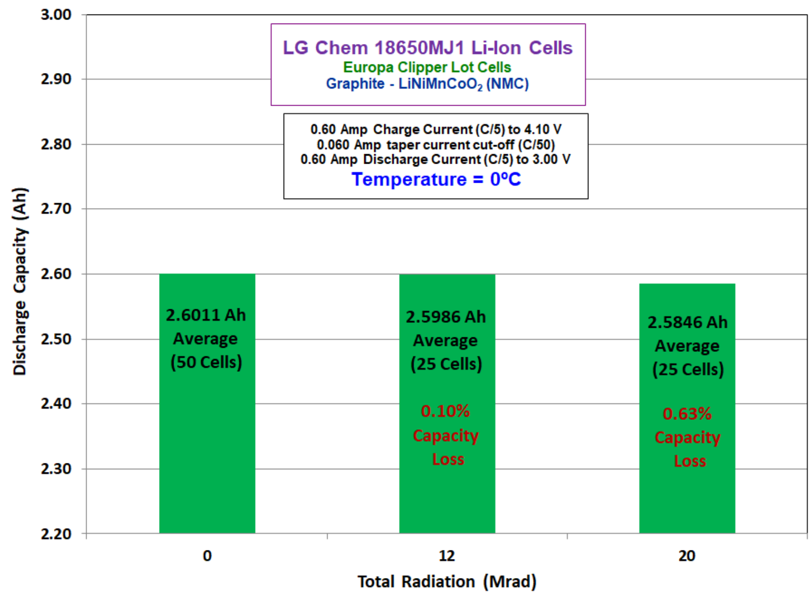


- Both cell types exhibit minimal impedance growth when exposed to high levels of radiation.
  - Only 1.23% impedance growth observed at 25°C with Moli ICRM cells when exposed to 20 Mrad TID
  - Only 3.79% impedance growth observed at 25°C with LG Chem MJ1 cells when exposed to 20 Mrad TID

NASA's Planned Europa Clipper Mission:
Li-Ion Cell Level Testing: Impact of Radiation Exposure

- ***Impact of ^{60}Co γ-Ray Irradiation: Reversible capacity at 0°C***
  - ***Comparison of Moli ICRM and LG Chem MJ1 18650-size cells***

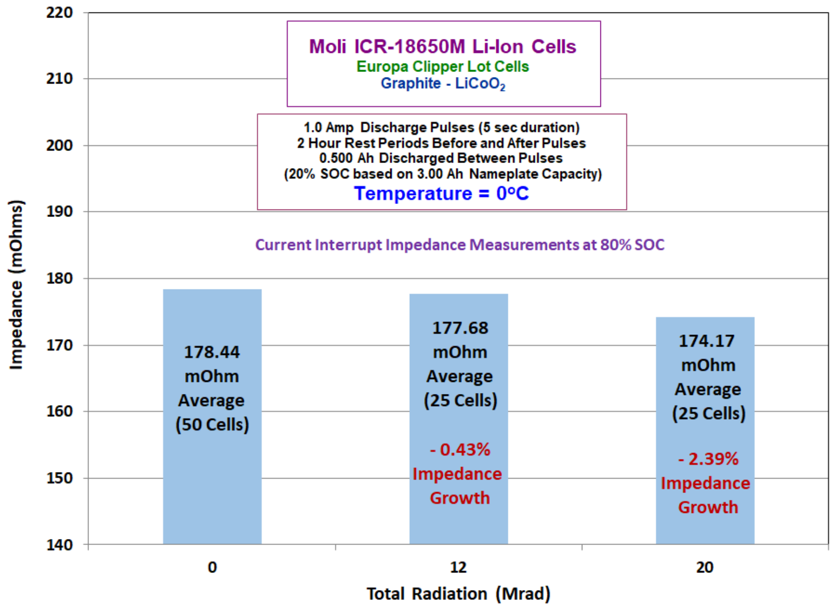


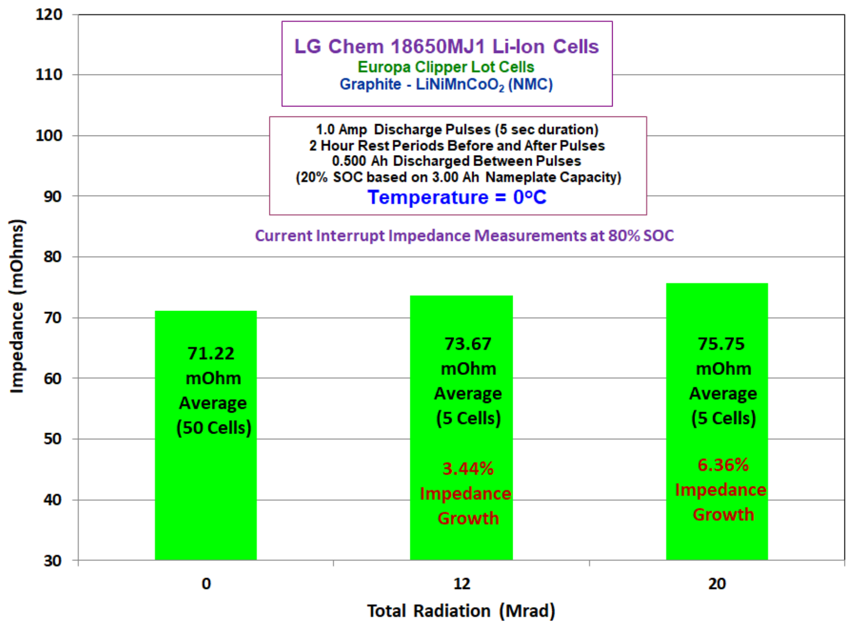


- Both cell types exhibit good resilience to high levels of radiation.
  - Only 0.86% capacity loss observed at 0°C with Moli ICRM cells when exposed to 20 Mrad TID
  - Only 0.63% capacity loss observed at 0°C with LG Chem MJ1 cells when exposed to 20 Mrad TID

NASA's Planned Europa Clipper Mission:
Li-Ion Cell Level Testing: Impact of Radiation Exposure

- **Impact of ^{60}Co γ-Ray Irradiation: Cell impedance at 0°C (80% SOC)**
  - **Comparison of Moli ICRM and LG Chem MJ1 18650-size cells**



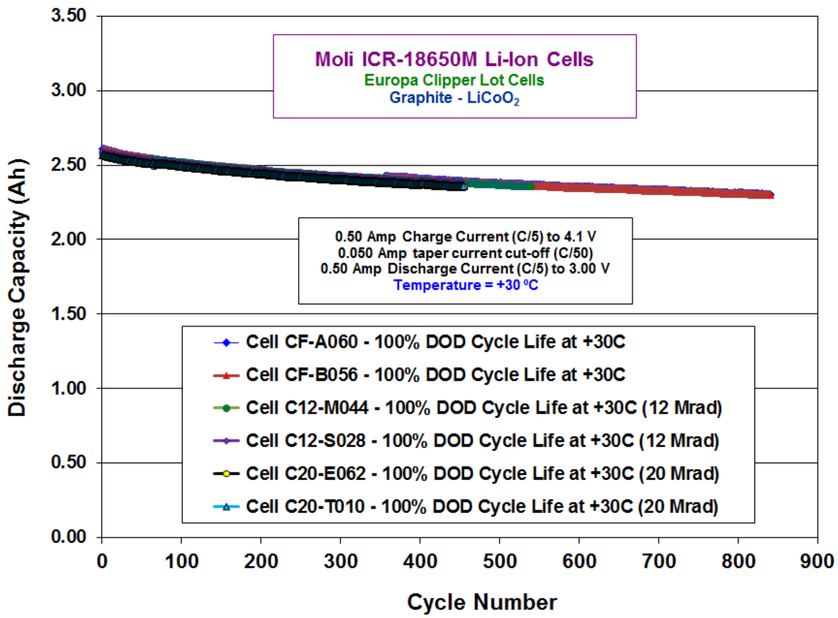


- Both cell types exhibit minimal impedance growth when exposed to high levels of radiation.
  - A 2.39% reduction in impedance was observed at 0°C with Moli ICRM cells when exposed to 20 Mrad
  - A 6.36% impedance growth observed at 0°C with LG Chem MJ1 cells when exposed to 20 Mrad TID
- Due to the high power design, the LG Chem MJI displays less than half the cell impedance.

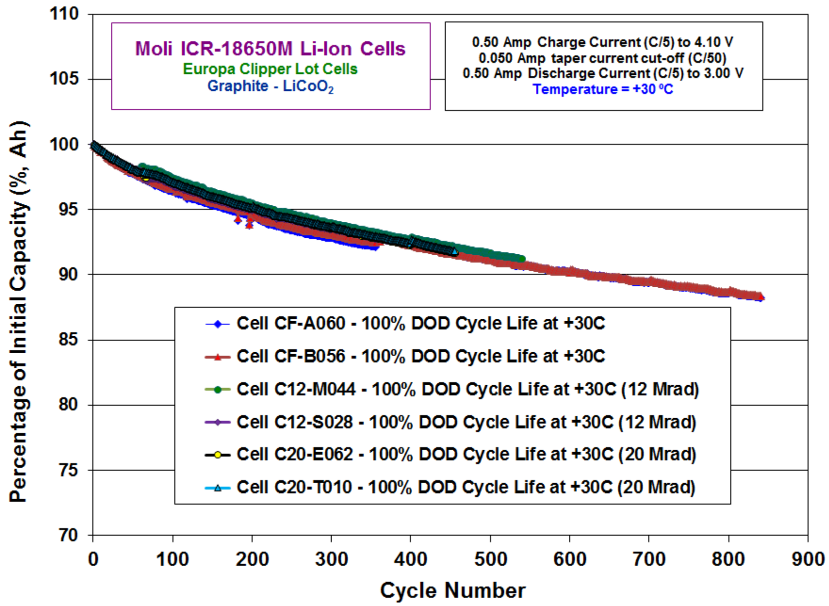
NASA's Planned Europa Clipper Mission:
Li-Ion Cell Level Testing: Cycle Life Performance

- ***Results of 100% DOD Cycle Life Testing +30°C of Moli ICRM Cells***

Discharge Capacity (Ah) at 30°C



Percentage of Initial Capacity (%) at 30°C

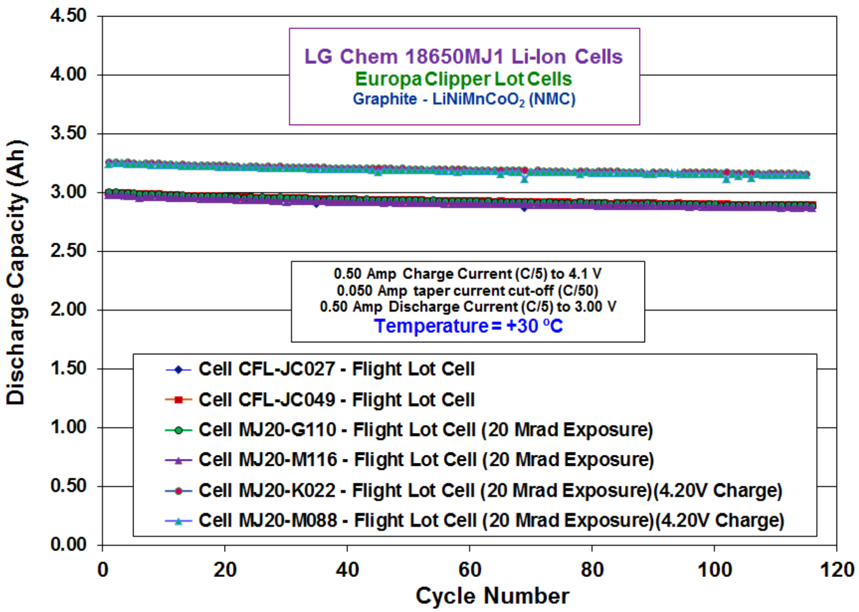


- **No significant impact of radiation upon the cycle life performance at +30°C was observed with E-One Moli ICRM cells up to 20 Mrad levels.**
  - **Baseline cells: After 300 cycles, cells displayed 2.4236 Ah and 92.98 % of initial capacity.**
  - **12 Mrad cells: After 300 cycles, cells displayed 2.4242Ah and 93.76 % of initial capacity.**
  - **20 Mrad cells: After 300 cycles, cells displayed 2.4220Ah and 94.40 % of initial capacity.**

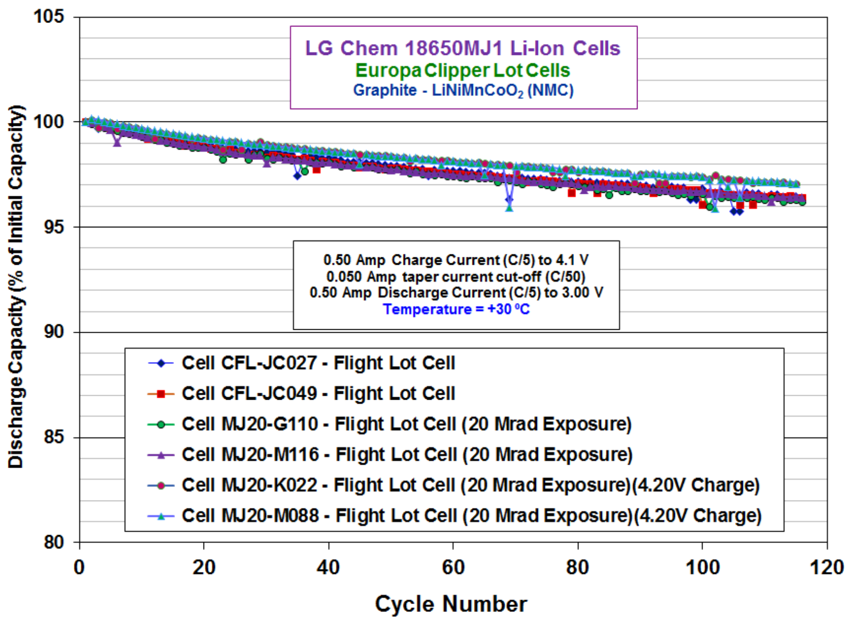
NASA's Planned Europa Clipper Mission:
Li-Ion Cell Level Testing: Cycle Life Performance

- *Results of 100% DOD Cycle Life Testing +30°C of LG Chem MJ1 Cells*

Discharge Capacity (Ah) at 30°C



Percentage of Initial Capacity (%) at 30°C

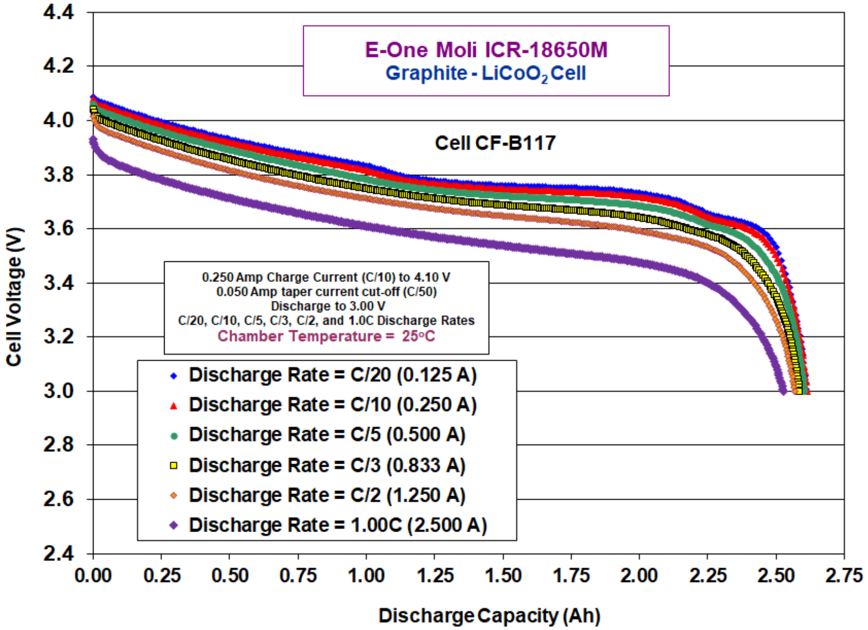


- **No significant impact of radiation upon the cycle life performance at +30°C was observed with LG Chem MJ1 cells up to 20 Mrad levels.**
  - Baseline cells : After 300 cycles, cells displayed 2.8829 Ah and 96.47 % of initial capacity.
  - 20 Mrad cells : After 300 cycles, cells displayed 2.8910 Ah and 96.66 % of initial capacity.
  - 20 Mrad cells : After 300 cycles, s cells displayed 3.1641 Ah and 97.38 % of initial (4.20V Charge)

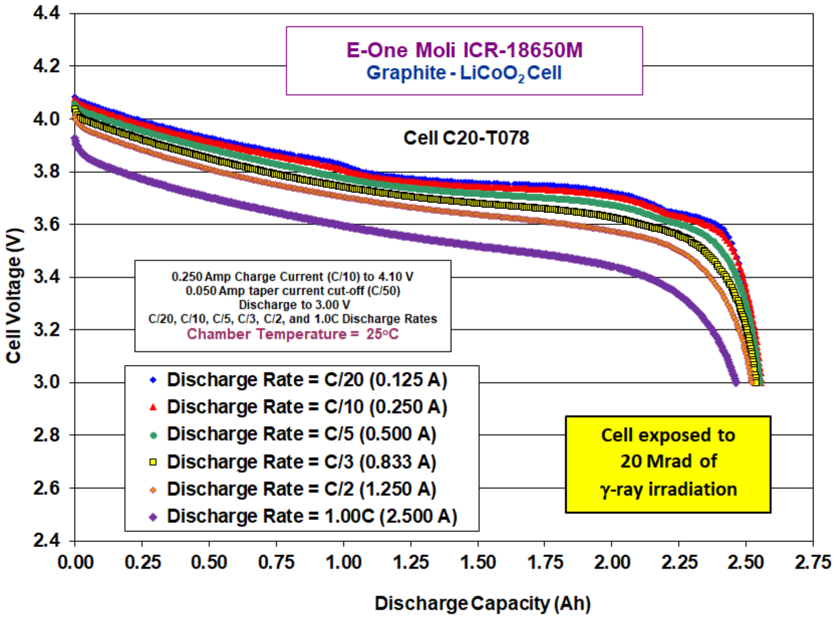
NASA's Planned Europa Clipper Mission:
Li-Ion Cell Level Testing: Discharge Rate Performance

- ***Results of discharge rate testing at 25°C: Impact of radiation***

Discharge Capacity (Ah) at 25°C
(No Irradiation)



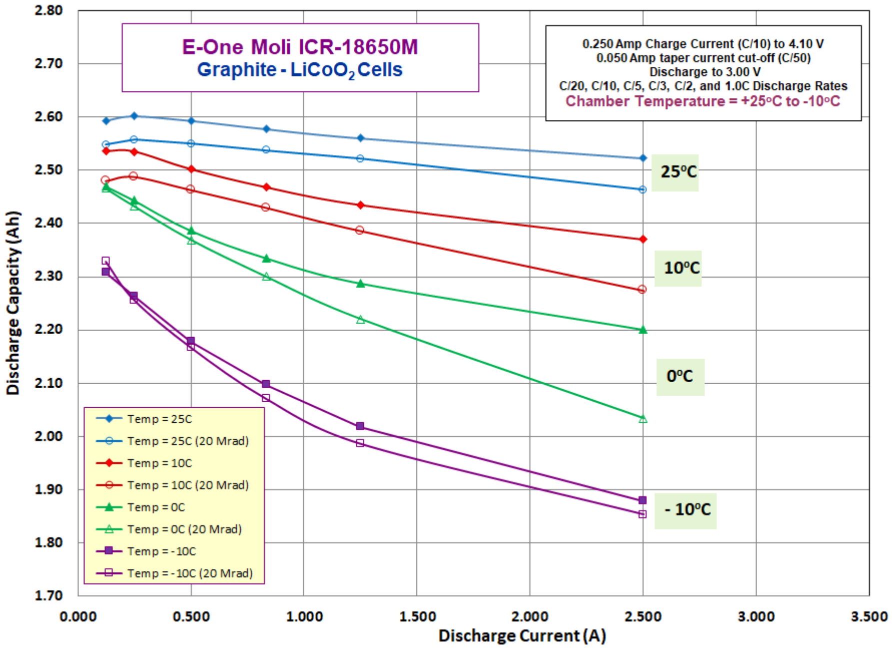
Discharge Capacity (Ah) at 25°C
(Exposed to 20 Mrad γ-rays)

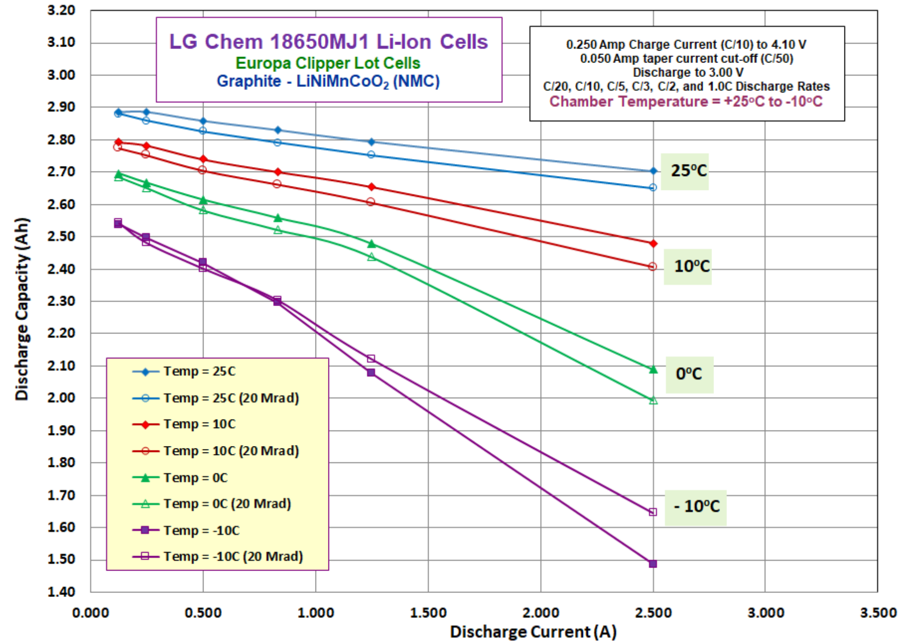


- **The impact of radiation upon the rate capability of E-One Moli is modest.**
  - **Upon irradiation with 20 Mrad, a decrease of approximately 1.5 to 2.3% capacity was observed.**
  - **The most significant decrease was observed at high rate (1C) and lower temperature.**

NASA's Planned Europa Clipper Mission:
Li-Ion Cell Level Testing: Discharge Rate Performance

- **_Results of discharge rate testing at different temperatures:_**
  - **_Impact of 20 Mrad g-ray irradiation_**





- **Both the E-One Moli ICRM and LG Chem MJ1 cells display good rate capacity as a function of temperature with only modest losses being observed.**
  - **Less performance loss was observed with the LG Chem MJ1 cells.**

NASA's Planned Europa Clipper Mission:
Li-Ion Module Level Testing: Cycle Life Performance

- ***Summary of String Level Testing :***
  - **Two different cell designs: (i) E-One Moli ICRM, and (ii) LG Chem MJ1**
  - **Modules consist of one string of 8 cells connected in series (8s1p modules)**
  - **Objective is evaluate the impact of γ-ray irradiation upon performance**
  - **Another objective is to validate cell dispersion characteristics with cycling**
  - **Three E-One Moli ICRM 8-cell strings were evaluated:**
    - **Baseline non-irradiated string**
    - **String exposed to 12 Mrad TID γ-rays**
    - **String exposed to 20 Mrad TID γ-rays**
  - **Two E-One Moli ICRM 8-cell strings were evaluated :**
    - **Baseline non-irradiated string (cells received Oct 2017 from ABSL)**
    - **String exposed to 20 Mrad TID γ-rays (cells received Nov 2018 from ABSL)**
      - **Cells irradiated prior to receipt at Sandia National Lab**
      - **Cells are from newer manufacturing lot from LG Chem**
  - **Cells that were selected were matched in terms of capacity and impedance**
  - **Good cell to cell consistency was observed with the lots received**

NASA's Planned Europa Clipper Mission:

Li-Ion Module Level Testing: Acceptance Testing

❑ Summary of Moli ICRM String Level Acceptance Testing: Part 1

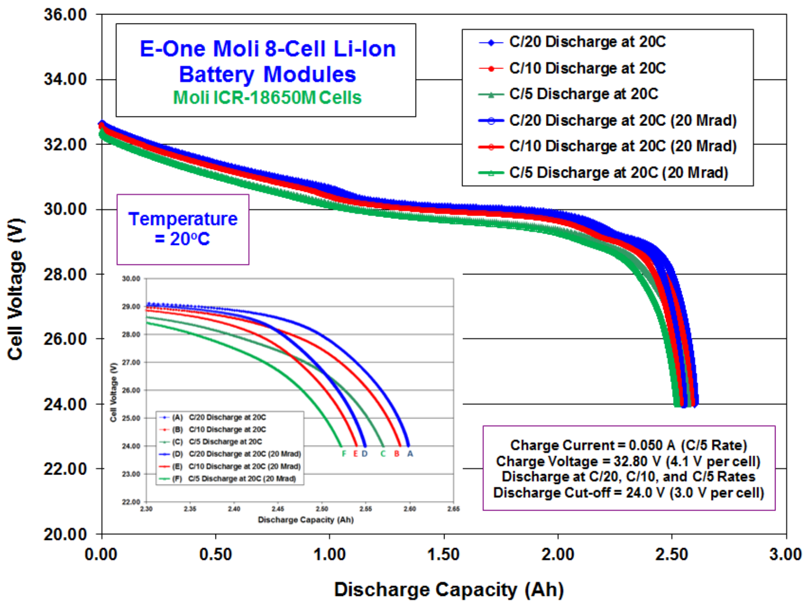
	Baseline Moli ICRM 8-Cell String				Moli ICRM 8-Cell String (12 Mrad)					Moli ICRM 8-Cell String (20 Mrad)				
	Capacity (Ah)	Percent of Initial (%)	Energy (Wh)	Percent Energy of Initial (%)	Capacity (Ah)	Percent of Initial (%)	Percent of Baseline (%)	Energy (Wh)	Percent Energy of Initial (%)	Capacity (Ah)	Percent of Initial (%)	Percent of Baseline (%)	Energy (Wh)	Percent Energy of Initial (%)
Initial Capacity and Impedance at 20°C (C/5, 32.8V)	2.5757	100.00	77.071	100.00	2.5411	100.00	98.66	76.010	100.00	2.5309	100.00	98.26	75.676	100.00
Initial Capacity and Impedance at 0°C (C/5, 32.8V)	2.3810	92.44	69.730	90.47	2.3441	92.25	98.45	68.601	90.25	2.3227	91.77	97.55	67.836	89.64
Capacity at +30°C (C/5, 32.8V)	2.6004	100.96	78.148	101.40	2.5648	100.93	98.63	77.051	101.37	2.5539	100.91	98.21	76.707	101.36
Capacity at +20°C (C/20, 32.8V)	2.5985	100.88	78.834	102.29	2.5598	100.73	98.51	77.656	102.17	2.5490	100.72	98.10	77.335	102.19
Capacity at +20°C (C/10, 32.8V)	2.5894	100.53	78.188	101.45	2.5501	100.35	98.48	76.996	101.30	2.5398	100.35	98.08	76.682	101.33
Capacity at +20°C (C/5, 32.8V)	2.5701	99.78	76.935	99.82	2.5319	99.64	98.51	75.768	99.68	2.5221	99.65	98.13	75.453	99.71
Capacity at +20°C (C/5, 33.6V)	2.8284	109.81	85.287	110.66	2.7988	110.14	98.95	84.394	111.03	2.7916	110.30	98.70	84.156	111.21
Capacity at 0°C (C/5, 32.8V)	2.4009	93.21	70.597	91.60	2.3643	93.04	98.48	69.456	91.38	2.343	92.57	97.58	68.684	90.76

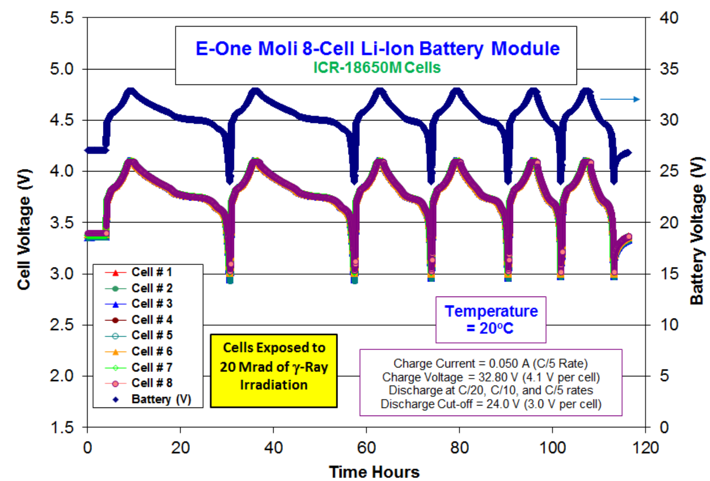
- **Approximately 1 to 1.5% capacity loss was observed when exposed to 12 Mrad and 1.5 to 2.0% capacity loss when exposed to 20 Mrad for the various conditions evaluated.**

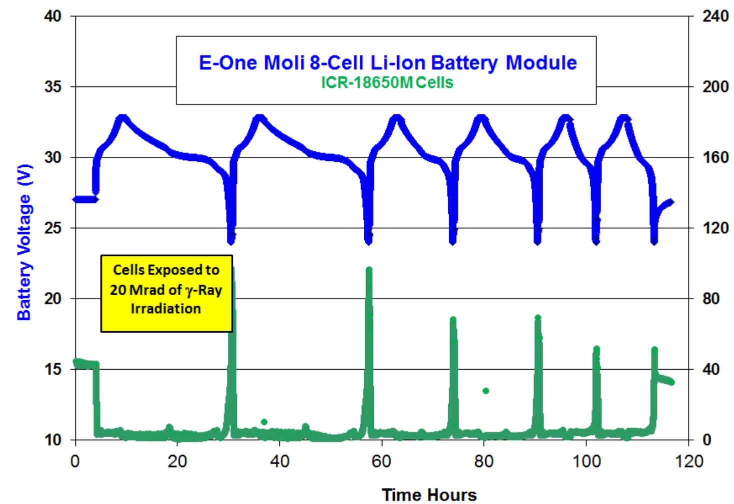
NASA's Planned Europa Clipper Mission:

Li-Ion Module Level Testing: Acceptance Testing

❑ ***Summary of Moli ICRM String Level Acceptance Testing: Rate Testing at +20°C***







- **Approximately 1 to 1.5% capacity loss was observed when exposed to 12 Mrad and 1.5 to 2.0% capacity loss when exposed to 20 Mrad for the various conditions evaluated.**
- **The cell dispersion characteristics were monitored throughout string level testing.**
- **Dispersion most dramatic at very low states of charge with the E-One Moli cells.**

NASA's Planned Europa Clipper Mission:

Li-Ion Module Level Testing: Acceptance Testing

❑ Summary of Moli ICRM String Level Acceptance Testing: Part 2

	Baseline Moli ICRM 8-Cell String				Moli ICRM 8-Cell String (12 Mrad)					Moli ICRM 8-Cell String (20 Mrad)				
	Capacity (Ah)	Percent of Initial (%)	Energy (Wh)	Percent Energy of Initial (%)	Capacity (Ah)	Percent of Initial (%)	Percent of Baseline (%)	Energy (Wh)	Percent Energy of Initial (%)	Capacity (Ah)	Percent of Initial (%)	Percent of Baseline (%)	Energy (Wh)	Percent Energy of Initial (%)
Capacity at +20°C after 72 hour OCV stand test	2.5454	98.82	76.170	98.83	2.5079	98.69	98.53	75.032	98.71	2.499	98.72	98.16	74.74	98.76
DC Impedance testing at +30°C and 0°C														
Repeat Capacity and Impedance at 20°C (C/5, 32.8V)	2.5580	99.31	76.596	99.38	2.5227	99.28	98.62	75.517	99.35	2.5134	99.31	98.26	75.218	99.39
Repeat Capacity and Impedance at 0°C (C/5, 32.8V)	2.3589	91.58	69.129	89.70	2.3291	91.65	98.74	68.281	89.83	2.32	91.66	98.35	67.971	89.82
Non-operation thermal cycling														
Repeat Capacity and Impedance at 20°C (C/5, 32.8V)	2.5512	99.05	76.392	99.12	2.5170	99.05	98.66	75.35	99.13	2.5079	99.09	98.30	75.059	99.18
Repeat Capacity and Impedance at 0°C (C/5, 32.8V)	2.3593	91.60	69.140	89.71	2.3309	91.73	98.80	68.337	89.91	2.321	91.70	98.37	67.994	89.85

- **After completing the acceptance testing, all modules only displayed ~ 1 % capacity loss at 20°C.**
- **All strings appear to display comparable degradation rates.**

NASA's Planned Europa Clipper Mission:

Li-Ion Module Level Testing: Acceptance Testing

❑ ***Summary of LG Chem String Level Acceptance Testing: Part 1***

	Baseline LG Chem MJ1 8-Cell String				LG Chem MJ1 8-Cell String (20 Mrad) (Newer Batch of Cells)				
	Capacity (Ah)	Percent of Initial (%)	Energy (Wh)	Percent Energy of Initial (%)	Capacity (Ah)	Percent of Initial (%)	Percent of Baseline (%)	Energy (Wh)	Percent Energy of Initial (%)
Capacity and Impedance at 20°C (C/5, 32.8V)	2.8439	100.00	83.054	100.00	2.9367	100.00	103.26	85.894	100.00
Capacity and Impedance at 0°C (C/5, 32.8V)	2.6339	92.62	76.308	91.88	2.6764	91.14	101.61	77.890	90.68
Capacity at +30°C (C/5, 32.8V)	2.8786	101.22	84.198	101.38	2.9918	101.88	103.93	87.541	101.92
Capacity at +20°C (C/20, 32.8V)	2.8889	101.58	84.919	102.24	3.0062	102.37	104.06	88.335	102.84
Capacity at +20°C (C/10, 32.8V)	2.8651	100.75	84.046	101.19	2.9762	101.35	103.88	87.343	101.69
Capacity at +20°C (C/5, 32.8V)	2.8304	99.53	82.646	99.51	2.9292	99.75	103.49	85.701	99.78
Capacity at +20°C (C/5, 33.6V)	3.1990	112.49	94.481	113.76	3.2011	109.00	100.07	94.474	109.99
Capacity at 0°C (C/5, 32.8V)	2.6533	93.30	76.859	92.54	2.6929	91.70	101.49	78.429	91.31

- **Due to the fact that the cells irradiated with 20 Mrad were from a newer manufacturing lot, higher capacity was observed compared to the baseline cells even though irradiated to high levels.**
- **Both cell lots appear to display similar degradation rates and rate capability.**

NASA's Planned Europa Clipper Mission:

Li-Ion Module Level Testing: Acceptance Testing

Summary of LG Chem String Level Acceptance Testing: Part 1

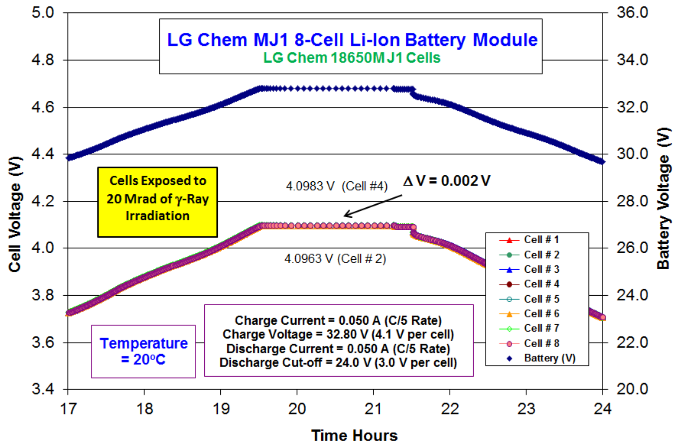
	Baseline LG Chem MJ1 8-Cell String				LG Chem MJ1 8-Cell String (20 Mrad) (Newer Batch of Cells)				
	Capacity (Ah)	Percent of Initial (%)	Energy (Wh)	Percent Energy of Initial (%)	Capacity (Ah)	Percent of Initial (%)	Percent of Baseline (%)	Energy (Wh)	Percent Energy of Initial (%)
Capacity at +20°C after 72 hour OCV stand	2.8182	99.10	82.187	98.96	2.9110	99.12	103.29	85.056	99.02
DC Impedance testing at +30°C and 0°C									
Repeat Capacity at 20°C (C/5, 32.8V)	2.8313	99.56	82.671	99.54	2.9241	99.57	103.28	85.565	99.62
Repeat Capacity at 0°C (C/5, 32.8V)	2.6429	92.93	76.553	92.17	2.6824	91.34	101.49	78.124	90.95
Non-operation thermal cycling									
Repeat Capacity at +30°C (C/5, 32.8V)	2.8658	100.77	83.802	100.90	2.9747	101.29	103.80	87.06	101.36
Repeat Capacity at +20°C (C/20, 32.8V)	2.8738	101.05	86.621	104.29	2.9858	101.67	103.90	87.77	102.18
Repeat Capacity at +20°C (C/10, 32.8V)	2.8521	100.29	83.657	100.73	2.9583	100.74	103.72	86.84	101.11
Repeat Capacity at +20°C (C/5, 32.8V)	2.8190	99.13	82.305	99.10	2.9145	99.24	103.39	85.29	99.30
Repeat Capacity at +20°C (C/5, 33.6V)	3.1848	111.99	94.086	113.28	3.1858	108.48	100.03	94.06	109.51
Repeat Capacity at 0°C (C/5, 32.8V)	2.6363	92.70	76.357	91.94	2.6782	91.20	101.59	78.02	90.83

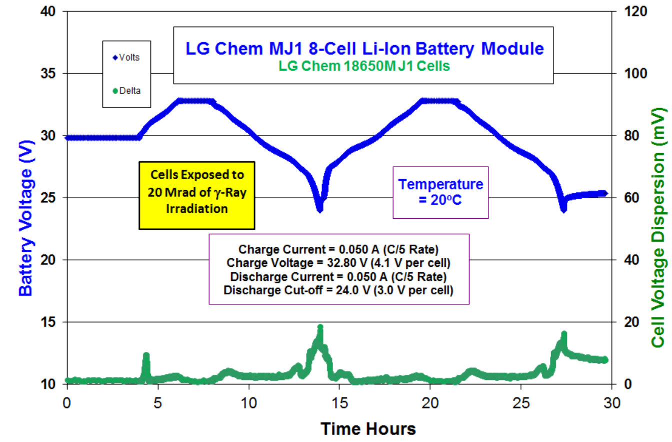
- **Due to the fact that the cells irradiated with 20 Mrad were from a newer manufacturing lot, higher capacity was observed compared to the baseline cells even though irradiated to high levels.**
- **Both cell lots appear to display similar degradation rates and rate capability.**

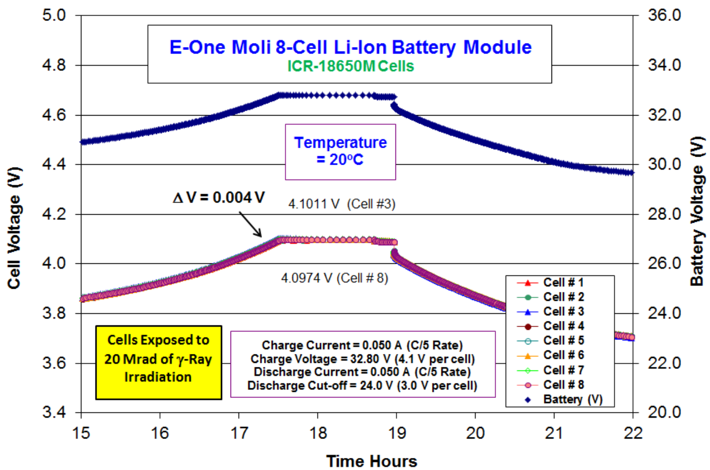
NASA's Planned Europa Clipper Mission:

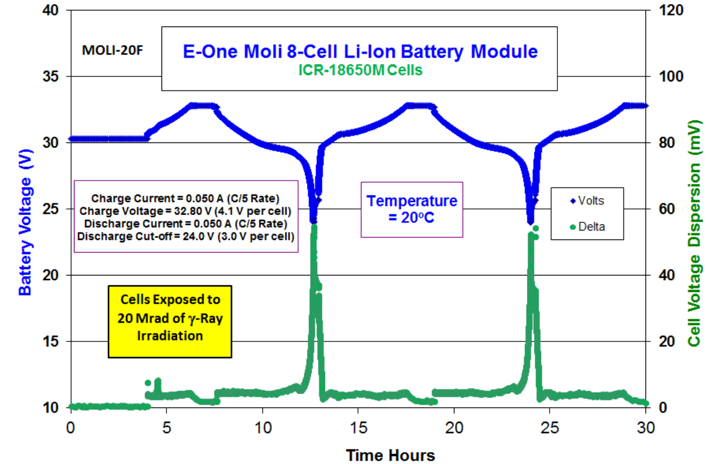
Li-Ion Module Level Testing: Acceptance Testing

❑ Summary of LG Chem String Level Acceptance Testing: Part 1







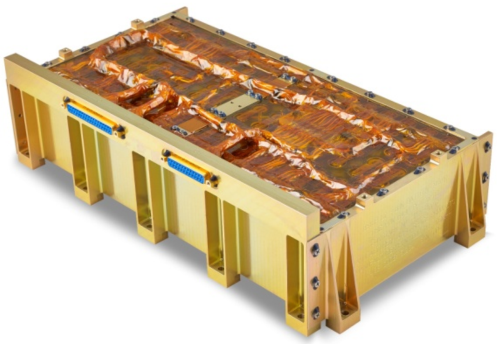


- **Excellent cell to cell uniformity was observed, especially with LG Chem MJ1 cells, with minimal cell voltage dispersion being observed after being exposed to 20 Mrad.**

NASA's Planned Europa Clipper Mission:
Pre-Qualification Battery Program: ABSL "Flight-like" 8s16p

Objective of Pre-Qualification Battery Program

- To address planetary protection and mission requirements, all batteries used for the Europa Clipper mission are expected to be exposed to high levels of radiation
- The Pre-Qualification Battery effort was initiated as a means to validate using ^{60}Co as planetary protection (PP) approach. Besides the cells, the electrochemically inert battery materials had not been exposed to high levels of radiation previously.
- To envelop PP and mission exposure, the battery was subjected to a total of 20 Mrad of γ-ray irradiation.
    - 12 Mrad for PP sterilization
    - 8 Mrad for Mission Requirements (4 Mrad TID x 2 for Qual)
- After irradiation, the battery was subjected to full qualification testing:
    - Functional characterization
    - Electrical characterization
    - Random vibration testing
    - Pyro-shock testing
    - Thermal vacuum testing
    - Post-environmental testing characterization



NASA's Planned Europa Clipper Mission:

Pre-Qualification Battery Program: ABSL "Flight-like" 8s16p

❑ *Test Flow of Pre-Qualification Battery Program:*

Design & Analysis Build

Inspection and initial acceptance
- ICD Verification
- Functional Checks

Irradiation with ^{60}Co γ-rays (20 Mrad)

Repeat of Functional Testing
- **Capacity Determination**

Structural Testing
- **Random Vibration**
- **Pyro-Shock**

Repeat of Functional Testing
- **Capacity Determination**

Thermal Testing
- Operational & Non-Operational Thermal Cycling in Vacuum
- Performance Testing

Inspection and final acceptance
- ICD Verification
- Functional Checks
- Capacity checks

- **Battery fabricated and testing at ABSL**
- **Battery populated with Moli ICRM cells**
- **8s16p design = 128 Li-ion cells (18650 size)**
- **Battery irradiated at Sandia National Lab**

NASA's Planned Europa Clipper Mission:
Pre-Qualification Battery Program: ABSL "Flight-like" 8s16p

- ***Results Pre-Qualification Battery Program:***
  - **Initial Acceptance Testing**
    - **Beginning of life capacity = 41.03 Ah**
  - **Irradiation with γ-Rays (20 Mrad)**
  - **Post-irradiation performance testing**
    - **Post-irradiation capacity = 40.01 Ah (2.49% total capacity loss from initial)**
  - **Random vibration testing (successfully passed)**
  - **Post-Random Vibration performance testing**
    - **Post-random vibe capacity = 39.95 Ah (2.63 % total capacity loss from initial)**
  - **Pyro-shock testing (successfully passed)**
  - **Post- Pyro-shock performance testing**
    - **Post-pyro shock capacity = 39.94A (2.66 % total capacity loss from initial)**
  - **Thermal vacuum testing (successfully passed)**
    - **Operational over temperature range of -15^{o}C to +45^{o}C**
  - **Post-thermal vacuum cycling performance testing**
    - **Post-thermal vacuum capacity = 39.30A (4.22 % total capacity loss from initial)**

➢ ***The 8s16p module passed all qualification testing***

Summary and Conclusions

- ***Evaluation of E-One Moli ICRM and LG Chem MJ1 Cells***
  - ***Both cell types exhibit good resilience to high levels of radiation.***
    - *Only 1.76% capacity loss observed at 25^{o}C with Moli ICRM cells when exposed to 20 Mrad*
    - *Only 0.40% capacity loss observed at 25^{o}C with LG Chem MJ1 cells when exposed to 20 Mrad*
  - ***No significant impact of radiation upon the cycle life performance at +30^{o}C was observed with E-One Moli ICRM cells up to 20 Mrad levels***
  - ***Both the E-One Moli ICRM and LG Chem MJ1 cells display good rate capacity as a function of temperature with only modest losses being observed.***
- ***Performance testing of 8-cell strings***
  - ***Excellent cell to cell uniformity was observed, especially with LG Chem MJ1 cells, with minimal cell voltage dispersion being observed after being exposed to 20 Mrad.***
  - ***Module level testing comparable with finding at the cell level.***
- ***Qualification testing of ABSL 8s16p module***
  - ***An ABSL 8s16p pre-qualification was subjected to 20 Mrad γ-rays***
  - ***Battery successfully passed full qualification testing, significantly lowering the risk of implementing γ-ray irradiation for planetary protection.***

Acknowledgments

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